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Brian W. Stump[1], Rong-Mao Zhou[2], Tae-Sung Kim[1], Yun-Tai Chen[3], Zhi-Xian Yang[3], Robert B. Herrmann[4], Relu Burlacu[5], Chris Hayward[1], and Kristine Pankow[5]

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Southern Methodist University
6425 BOAZ, Rm G05, Perkins Administration
Dallas, TX 75275-0001

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14. ABSTRACT
We continued the operation of the Southern Methodist University-Institute of Geophysics, China Earthquake Administration (SMU-IGPCEA) broadband seismic network through May 2008 using Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) instrumentation. The operating network included three stations northwest of Beijing and 10 stations in Xiuyan, Liaoning Province, NE China. At the end of May, the PASSCAL instrumentation was returned to the U.S. During the 5.5-year operation, we collected approximately 600 Gb of miniSEED data. Most of the data have been archived at the Incorporated Research Insitutes for Seismology (IRIS) data center. This high-quality dataset has already provided us the opportunity to study the detailed velocity structure beneath the Huailai Basin and Haicheng in NE China using both teleseismic and regional signals. We are expanding our joint inversion of teleseismic receiver functions and surface wave phase velocities for crustal shear velocity structure from the Huailai Basin to the Huabei area using data from SMU-IGPCEA broadband seismic network with additional data provided by 48 broadband seismic stations in this region. Preliminary results show that the phase velocities under this region range from 3.2 to 4.0 km/sec over a period range of 10–90 sec. The joint inversion study will allow us to quantify the spatial variability of the shear velocity structure under this broader region in detail providing a better characterization of regional propagation paths. Infrasound gauges originally destined for China were installed in three arrays in Utah. Data from these arrays are telemetered in real-time to the University of Utah. Each array consists of four infrasound sensors with approximately 100 m separation sampled at 100 samples/s. In the summer of 2007, a consortium participated in the design and installation phases of a 4-week experiment in northern Utah to record four rocket motor detonations at the Utah Test and Training Range at Hill AFB. These blasts were recorded on the existing dense distribution of Utah regional seismic stations, six infrasound arrays, the regional EarthScope transportable array (TA) stations, and a temporary field deployment of PASSCAL instruments with infrasound microphones distributed from 200 m to more than 200 km from the source. Balloon launches of rawinsondes were conducted near the shot time and tracked in order to experimentally quantify the temperatures and winds of the shallow atmosphere. The distance range of the observations includes the shadow zone where standard atmospheric models predict no infrasound arrivals (McKenna, 2005). The Utah infrasound network recorded infrasound signals in this shadow zone from the four rocket motor detonations. The preliminary analysis of observed infrasound signals shows arrivals at local (<100 km) and regional distances (140–210 km). Group velocities of local arrivals are estimated around at 350 m/s while those of regional arrivals are relatively slower (300 to 280 m/sec). The mean phase velocity in the local distance range is slightly slower (358.7 ±9.8 m/sec) compared to that at the regional distance range (385.5 ±7.6 m/sec). The Utah observations also document the focusing of infrasound energy around 50 km. These observed infrasound arrivals and amplitude anomalies at local distances are successfully modeled using the parabolic equation (PE) with the shallow atmosphere quantified by the balloon data. The PE results confirm that a shallow inverted atmospheric layer exists to a height of 1 to ~2 km and functions as a duct that traps infrasound energy at local distances and focuses energy at around 50 km.

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SHEAR VELOCITY STRUCTURE IN NE CHINA AND CHARACTERIZATION OF INFRASOUND WAVE PROPAGATION IN THE 1-210 KILOMETER RANGE

Brian W. Stump[1], Rong-Mao Zhou[2], Tae-Sung Kim[1], Yun-Tai Chen[3], Zhi-Xian Yang[3], Robert B. Herrmann[4], Relu Burlacu[5], Chris Hayward[1], and Kristine Pankow[5]

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ABSTRACT

We continued the operation of the Southern Methodist University-Institute of Geophysics, China Earthquake Administration (SMU-IGPCEA) broadband seismic network through May 2008 using Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) instrumentation. The operating network included three stations northwest of Beijing and 10 stations in Xiuyan, Liaoning Province, NE China. At the end of May, the PASSCAL instrumentation was returned to the U.S. During the 5.5-year operation, we collected approximately 600 Gb of miniSEED data. Most of the data have been archived at the Incorporated Research Insitutes for Seismology (IRIS) data center. This high-quality dataset has already provided us the opportunity to study the detailed velocity structure beneath the Huailai Basin and Haicheng in NE China using both teleseismic and regional signals. We are expanding our joint inversion of teleseismic receiver functions and surface wave phase velocities for crustal shear velocity structure from the Huailai Basin to the Huabei area using data from SMU-IGPCEA broadband seismic network with additional data provided by 48 broadband seismic stations in this region. Preliminary results show that the phase velocities under this region range from 3.2 to 4.0 km/sec over a period range of 10–90 sec. The joint inversion study will allow us to quantify the spatial variability of the shear velocity structure under this broader region in detail providing a better characterization of regional propagation paths.

Infrasound gauges originally destined for China were installed in three arrays in Utah. Data from these arrays are telemetered in real-time to the University of Utah. Each array consists of four infrasound sensors with approximately 100 m separation sampled at 100 samples/s. In the summer of 2007, a consortium participated in the design and installation phases of a 4-week experiment in northern Utah to record four rocket motor detonations at the Utah Test and Training Range at Hill AFB. These blasts were recorded on the existing dense distribution of Utah regional seismic stations, six infrasound arrays, the regional EarthScope transportable array (TA) stations, and a temporary field deployment of PASSCAL instruments with infrasound microphones distributed from 200 m to more than 200 km from the source. Balloon launches of rawinsondes were conducted near the shot time and tracked in order to experimentally quantify the temperatures and winds of the shallow atmosphere. The distance range of the observations includes the shadow zone where standard atmospheric models predict no infrasound arrivals (McKenna, 2005). The Utah infrasound network recorded infrasound signals in this shadow zone from the four rocket motor detonations. The preliminary analysis of observed infrasound signals shows arrivals at local (<100 km) and regional distances (140–210 km). Group velocities of local arrivals are estimated around at 350 m/s while those of regional arrivals are relatively slower (300 to 280 m/sec). The mean phase velocity in the local distance range is slightly slower (358.7 ±9.8 m/sec) compared to that at the regional distance range (385.5 ±7.6 m/sec). The Utah observations also document the focusing of infrasound energy around 50 km. These observed infrasound arrivals and amplitude anomalies at local distances are successfully modeled using the parabolic equation (PE) with the shallow atmosphere quantified by the balloon data. The PE results confirm that a shallow inverted atmospheric layer exists to a height of 1 to ~2 km and functions as a duct that traps infrasound energy at local distances and focuses energy at around 50 km.

OBJECTIVES

The primary goal of the collaborative study between the SMU and the IGPCEA (formerly IGCSB) is to develop a database of seismic events in NE China, to refine crust and upper mantle structure in Yanqing-Huailai Basin and Haicheng area, to understand source characterization of natural and human-induced events, and to separate source and propagation path effects at regional distances.

A second objective of this project is the instrumental quantification of seismic and infrasound signals observed at regional distances. The focus in this case is on manmade and natural sources that generate both infrasound and seismic waves. Initially, plans called for infrasound gauges to be co-located with the seismometers deployed in NE China. After acquisition of the infrasound gauges, the deployment was made in the U.S., collocating infrasound gauges with seismometers operated in conjunction with University of Utah Seismograph Stations. These data are being used to assess atmospheric propagation path effects from known explosion sources.

RESEARCH ACCOMPLISHED

NE China

We continued the operation of the SMU-IGPCEA broadband seismic network through May 2008 using PASSCAL instrumentation. The deployment of the broadband seismic network operated by SMU and IGPCEA since November 2002 included 14 stations in and around Beijing, Huabei Province and 10 stations in the Haicheng area, Liaoning Province, China (Zhou et al., 2006). At the end of May the PASSCAL instrumentation was returned to the US. During the 5.5-year operation time period, we collected approximately 600 Gb of good-quality miniSEED data. Most of the data has been archived at the IRIS data center. This high-quality dataset has already provided us the opportunity to study the detailed velocity structure beneath Huailai Basin and Haicheng in the NE China area, using both teleseismic and regional signals (Zhou et al., 2006).

We are expanding our joint inversion of teleseismic receiver functions and surface wave phase velocities for crustal shear velocity structures from the Huailai Basin to the Huabei area using data from the SMU-IGPCEA broadband seismic network, supplemented by data provided by 48 broadband seismic stations that make up the Huabei Seismic Network, as illustrated in Figure 1. The new seismic work that is discussed in this paper focuses on preliminary analysis of this new dataset.

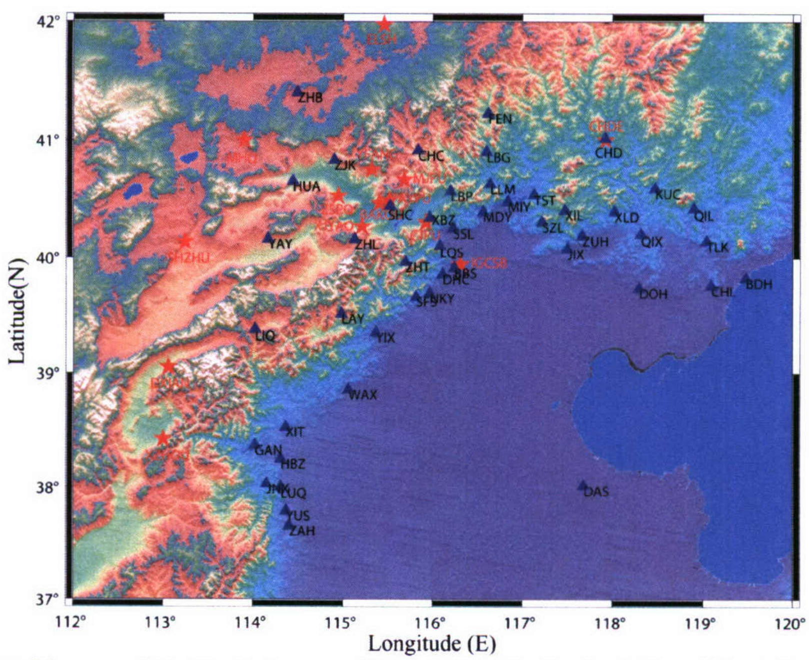

Figure 1. Topographic map of the Huabei area, with broadband seismic stations (blue triangles: Huabei Seismic Network; red stars: SMU-IGPCEA stations in this region).

Twenty-one teleseismic events with great circle epicentral distances in the range of 30^{o} to 80^{o} from 2004 to 2005 have been chosen for receiver function and surface wave analysis. Source parameters of these events were obtained from the Preliminary Determination of Epicenters (PDE) bulletins provided by the United States Geological Survey (USGS) National Earthquake Information Center (NEIC) and are listed in Table 1. Figure 2 is the map of the 21 teleseismic events (red dots).

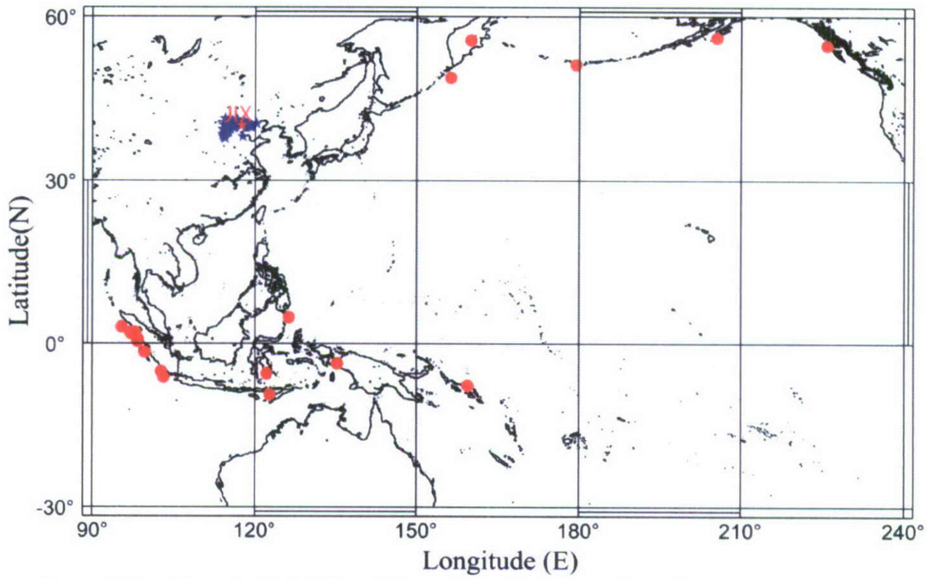

Figure 2. Map of event locations (red dots) and broadband stations (stars).

Table 1. List of event parameters

Event Code	Date (Y-M-D)	Time (hhmmss.mm)	Latitude (°)	Longitude (°)	Magnitude	Depth (km)
2004039	2004-02-08	085851.80	-3.66	135.34	6.9	25
2004107	2004-04-16	215705.41	-5.21	102.72	6.0	44
2004114	2004-04-23	015030.22	-9.36	122.84	6.7	65
2004162	2004-06-10	151957.75	55.68	160.00	6.9	188
2004180	2004-06-28	094947.00	54.80	-134.25	6.8	20
2004353	2004-12-18	064619.87	48.84	156.31	6.2	11
2005022	2005-01-22	203017.35	-7.73	159.48	6.5	29
2005046	2005-02-15	144225.85	4.76	126.42	6.6	39
2005050	2005-02-19	000443.59	-5.56	122.13	6.5	10
2005089	2005-03-30	161941.10	2.99	95.41	6.4	22
2005093	2005-04-03	005921.42	0.37	98.32	6.0	30
2005093-2	2005-04-03	031056.47	2.02	97.94	6.3	36
2005099	2005-04-09	151627.89	56.17	-154.52	6.0	14
2005100	2005-04-10	102911.28	-1.64	99.61	6.7	19
2005100-2	2005-04-10	172439.40	-1.59	99.72	6.4	30
2005106	2005-04-16	163803.90	1.81	97.66	6.4	31
2005130	2005-05-10	010905.10	-6.23	103.14	6.4	17
2005134	2005-05-14	050518.48	0.59	98.46	6.8	34
2005139	2005-05-19	015452.85	1.99	97.04	6.9	30
2005165	2005-06-14	171016.64	51.23	179.41	6.8	51
2005186	2005-07-05	015202.95	1.82	97.08	6.8	21

Receiver functions were extracted from all 21 events in Table 1 and Figure 2. Station JIX recorded 18 of 21 events, and the radial component receiver functions with Gaussian parameter, $\alpha = 1.0$, at JIX are presented in Figure 3 to illustrate the quality of the data and resulting receiver functions.

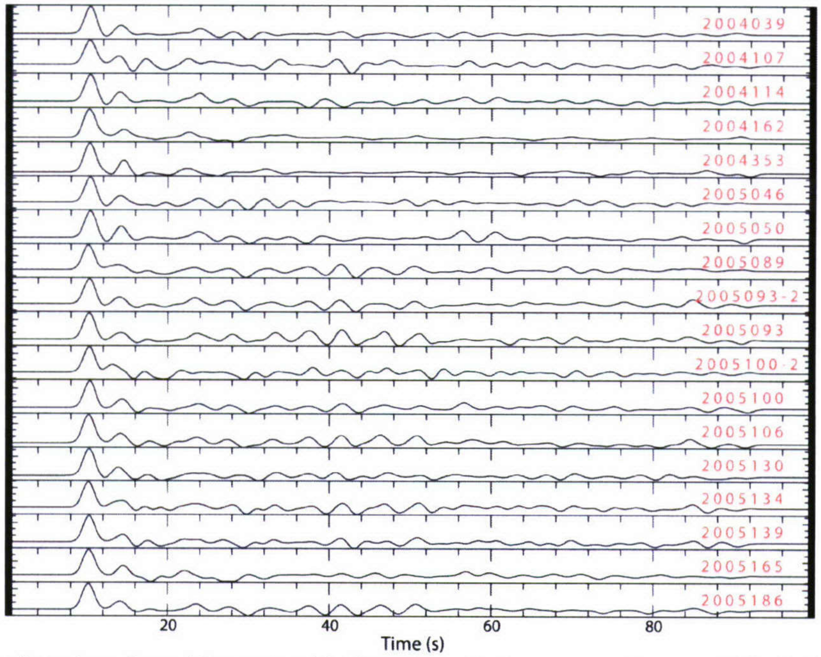

Figure 3. Receiver functions from 18 events with Gaussian window parameters α = 1.0, at station JIX.

The phase velocities under this region are obtained using the fundamental mode Rayleigh waves extracted from raw data and the technique described by McMechan and Yedlin (1981). Figure 4 presents the averaged phase velocities in this region from analyzed events, and it ranges from 3.1 to 4.0 km/sec over period range of 10–90 sec.

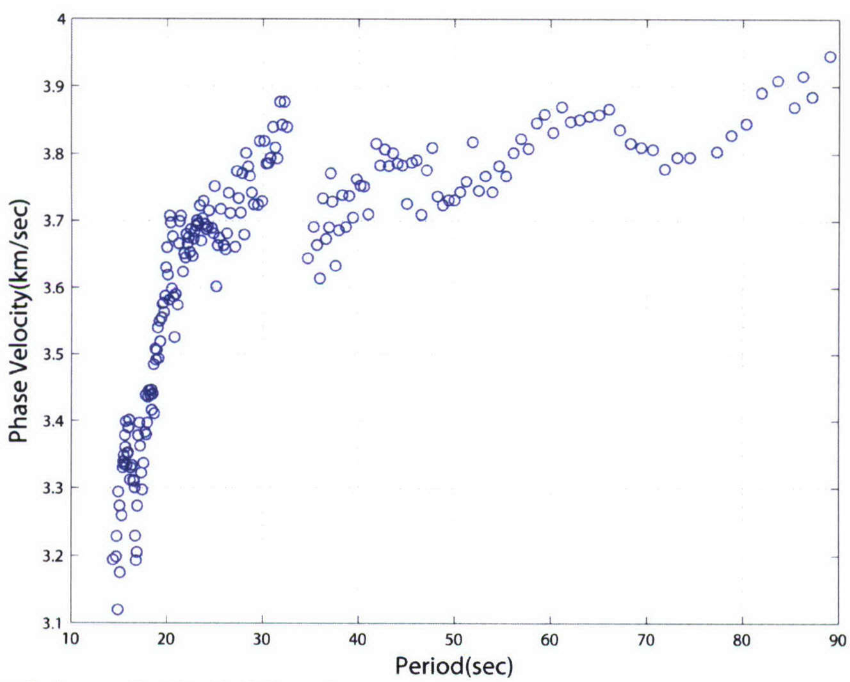

Figure 4. Averaged phase velocities in this region.

Work continues expanding the database from this new set of Chinese stations as well as the development of crust and upper mantle models based upon the new data source.

Infrasound

In the summer of 2007, a consortium participated in a 4-week experiment in northern Utah, designed to record regional seismo-acoustic signals including rocket motor detonations at the Hill AFB Utah Test and Training Range (UTTR) (Stump et al., 2007a; Stump at al., 2007b). The dense distribution of existing seismic stations, which is part of the regional network operated and maintained by the University of Utah Seismograph Stations (UUSS) and the temporarily installed seismic stations in Utah under the EarthScope National Science Foundation (NSF) project, were augmented 14 single acoustic stations and 6 acoustic arrays that our consortium deployed (Figure 5), including the 3 acoustic arrays supported under this contract. Equipment supplied by the PASSCAL program was used to make the infrasound measurements. This deployment of seismic and acoustic instruments at UTTR gives a unique opportunity to study the generation and propagation of local-to-regional seismic and low frequency acoustic energy from shallow sources. The seismic and acoustic stations were distributed in the 200 m to 210 km distance range. Rawinsondes were launched to measure the variation in temperature, wind speed, and wind direction from the surface up to 20 km.

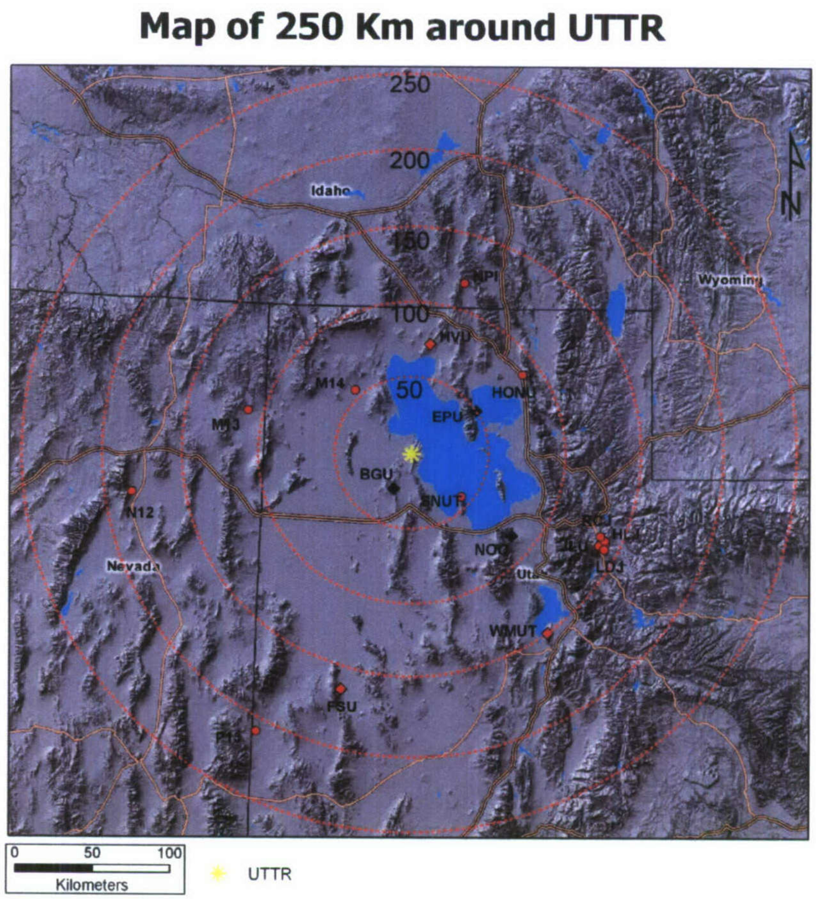

Figure 5. Map of seismo-acoustic station distribution in Utah. The yellow star is UTTR. Solid black diamonds are permanent infrasound arrays supported under this project, red diamonds are temporary infrasound arrays, and red circles are locations of single infrasound gauges.

During the 4-week deployment we recorded four rocket motor detonations (~50,000 TNT equivalent each), with duration magnitudes between 1.8 and 2.1 (UUSS). One example of a typical seismo-acoustic recording illustrates clear seismic arrivals with acoustic signals at station FSU (Figure 6). From the collocated seismo-acoustic sensors, it

was observed that rocket motor detonations generated air-to-ground coupling even at the maximum distance range of our experiment (~210 km).

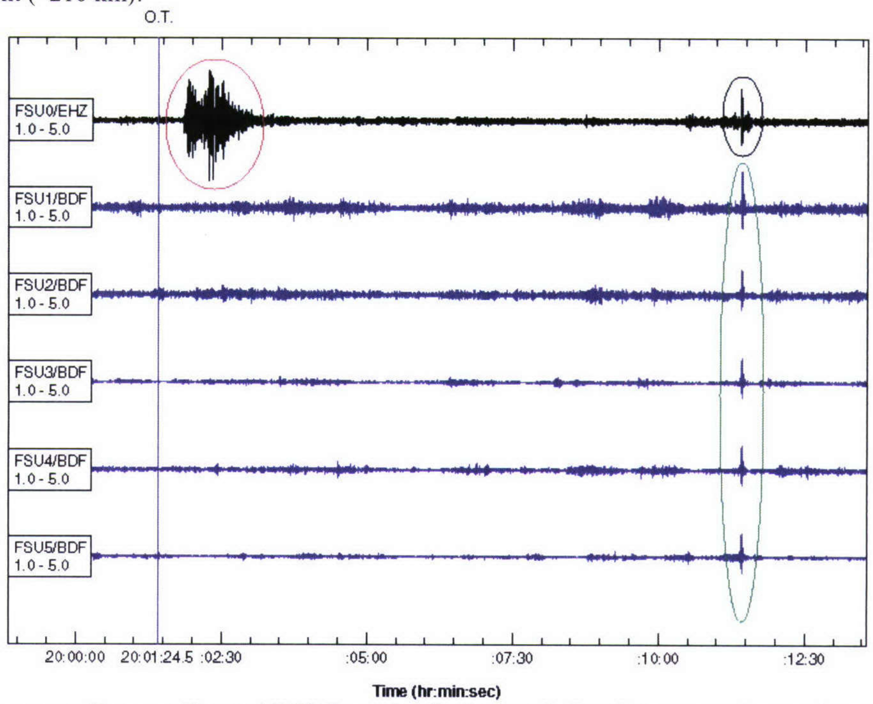

Figure 6. Seismo-acoustic recordings at FSU from the first recorded rocket motor detonation on August 1, 2007, 20:01:24.5. Seismic signals (red circle) are illustrated with acoustic signals (green circle) as well as air-to-ground coupled seismic signal (black circle).

Comparison of amplitude and waveforms at BGU from the four explosions illustrates that the seismic signals are repeatable while acoustic signals are not, even though the sizes and locations of sources are nearly the same (Figure 7). Waveforms at other stations are consistent with those from BGU. These observations suggest that the controlling factors on the infrasound amplitudes and waveforms are more than the size and location of sources and may require a time-varying atmospheric propagation path.

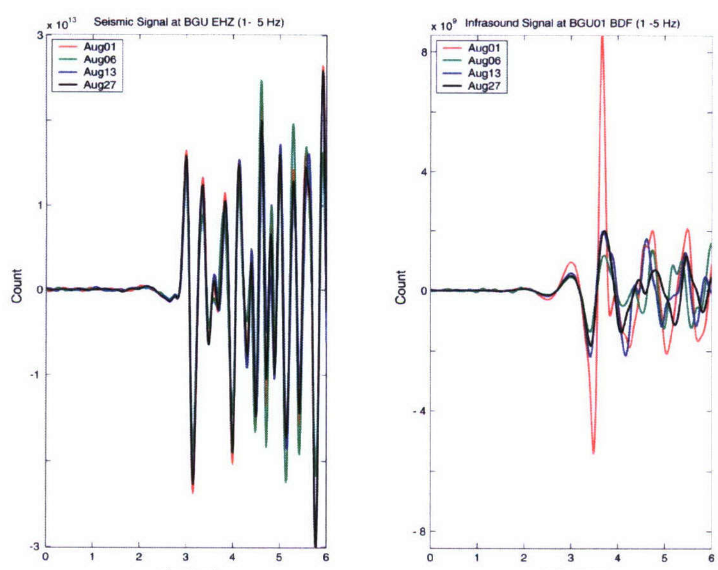

Figure 7. Seismic signals (1-5 Hz) from the four detonations (left) are compared with acoustic signals (1–5 Hz, right) recorded at BGU.

Record sections of acoustic signals from the four explosions are reproduced in Figure 8. We classify the infrasonic arrivals into two groups: (1) arrivals at a distance less than 100 km (local arrivals) and (2) those between 150 and 210 km (regional arrivals).

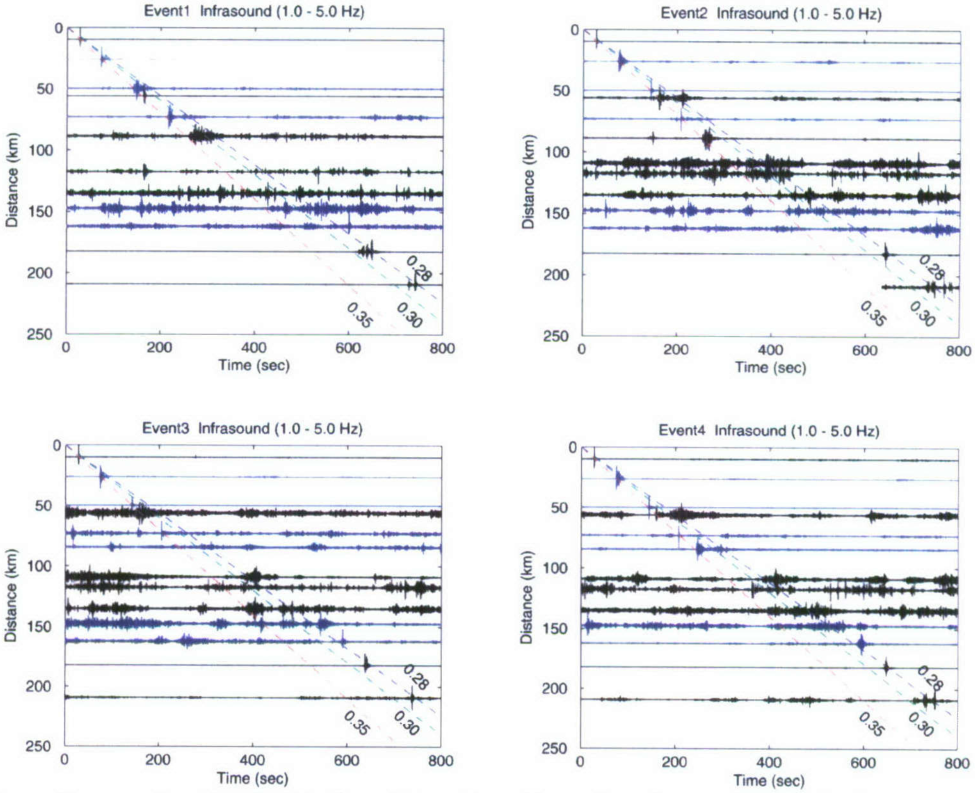

Figure 8. Acoustic record section for the four detonations. Record sections consist of single stations (black) and array data (blue).

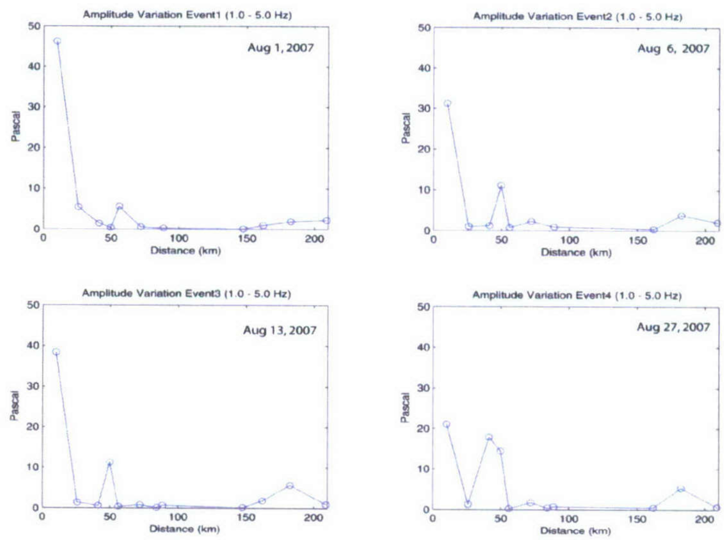

Figure 9: Range effects of acoustic signals (1–5 Hz) from the four detonations. Maximum amplitude in the 1–5 Hz band is plotted.

Estimates of group velocity at local distances are near 350 m/sec while those of regional distances vary from 280 to 300 m/sec. Using the acoustic arrays, mean phase velocity in the local distance range is 359 ± 9.8 m/sec, which is near the speed of sound at the surface, while that of the regional distance is 386 ± 7.6 m/sec, consistent with turning rays from the stratosphere or thermosphere. The backazimuth mean error estimate for all the explosions using data from the local distance range was 2.4°, while that using regional distance data was 5.5°. Figure 9 illustrates strong focusing and defocusing effects as a function of range. Higher amplitudes are observed at around 50 km although the exact location of the focus changes by as much as 10 to 20 km from day to day and thus can strongly impact the absolute amplitudes at a particular station for the four explosions.

The PE modeling method (Lingevitch et al., 2002) using local atmospheric profiles was used to investigate infrasound arrivals and amplitude variations in the local distance range. The software used for the modeling was InfraMAP (Norris and Gibson, 2006). The local atmospheric file was obtained using balloon launches of rawinsondes from an island in the Great Salt Lake at or near the detonation time. Figure 10 illustrates different 1-D velocity models that change as a function of propagation direction and time based on the empirical atmospheric data for the four days when the explosions were conducted.

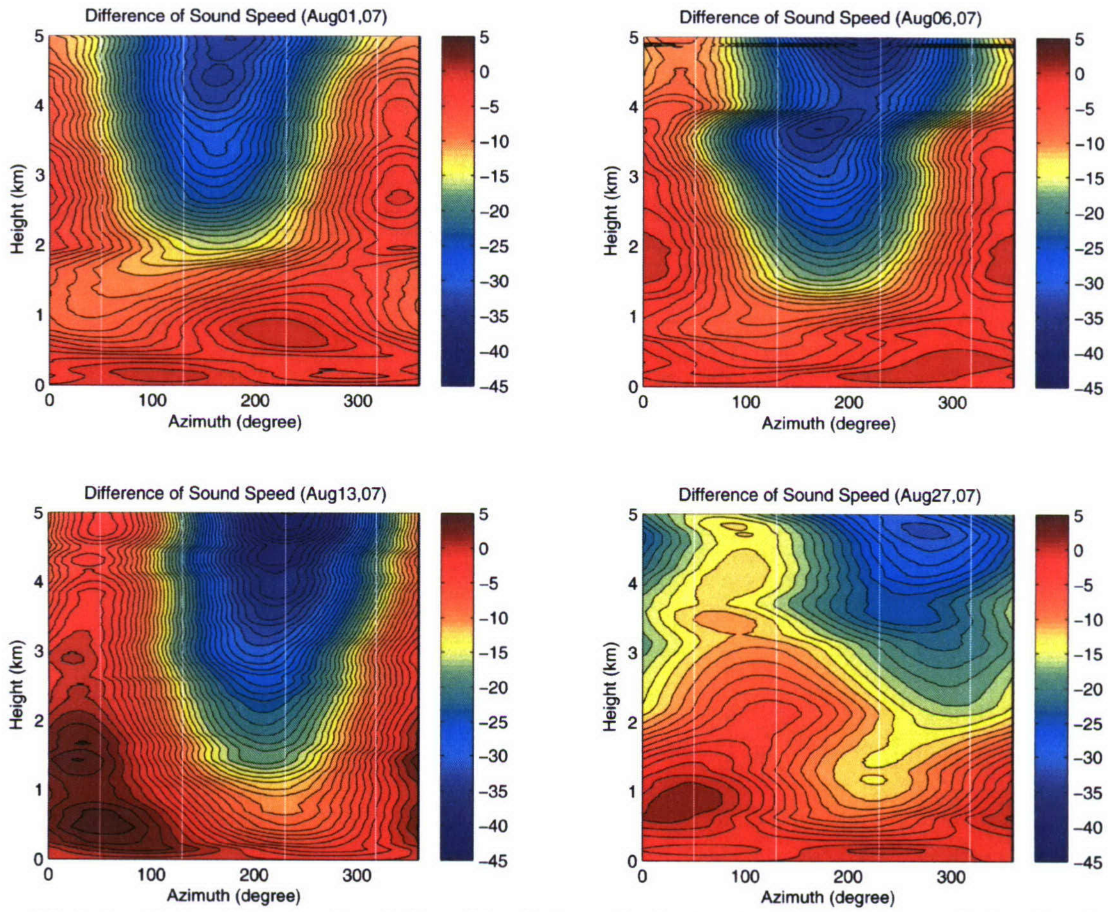

Figure 10. Azimuthal and temporal variation of local atmospheric structure for the four explosion days based on rawinsonde launched at of near the explosion time. The color scale represents the difference between the speed of sound at a specific height and that of surface (C_h-C_0, unit: m/sec).

PE modeling was performed at three different frequencies (0.25, 1.0, and 3.0 Hz) using the source-station specific directions and the1-D local atmospheric structure along that direction based on the rawinsonde data. One example of these PE solutions for the August 6, 2007, 20:00:00 hour GMT shows that there is a shallow duct (~2 km) for acoustic energy along the source to receiver azimuth of 45°, while the calculations along the other two directions

(113° and 288°) do not predict trapped energy (Figure 11). These modeling results are consistent with the ranges and azimuths along which infrasound arrivals were identified in the local distance range, out to 100 km. For the three other shots, PE modeling produced predictions based on energy trapped in a shallow inverted layer between 1 and 2 km in height that were consistent with observations on these other days as well. The PE modeling suggests that observed acoustic arrivals at local distances (<100 km) and focusing of energy are related to the trapped acoustic energy between the surface and the shallow inverted atmospheric layer. For modeling the regional arrivals (150–210 km), the PE method and ray tracing with the G2S profile will be performed in a future study.

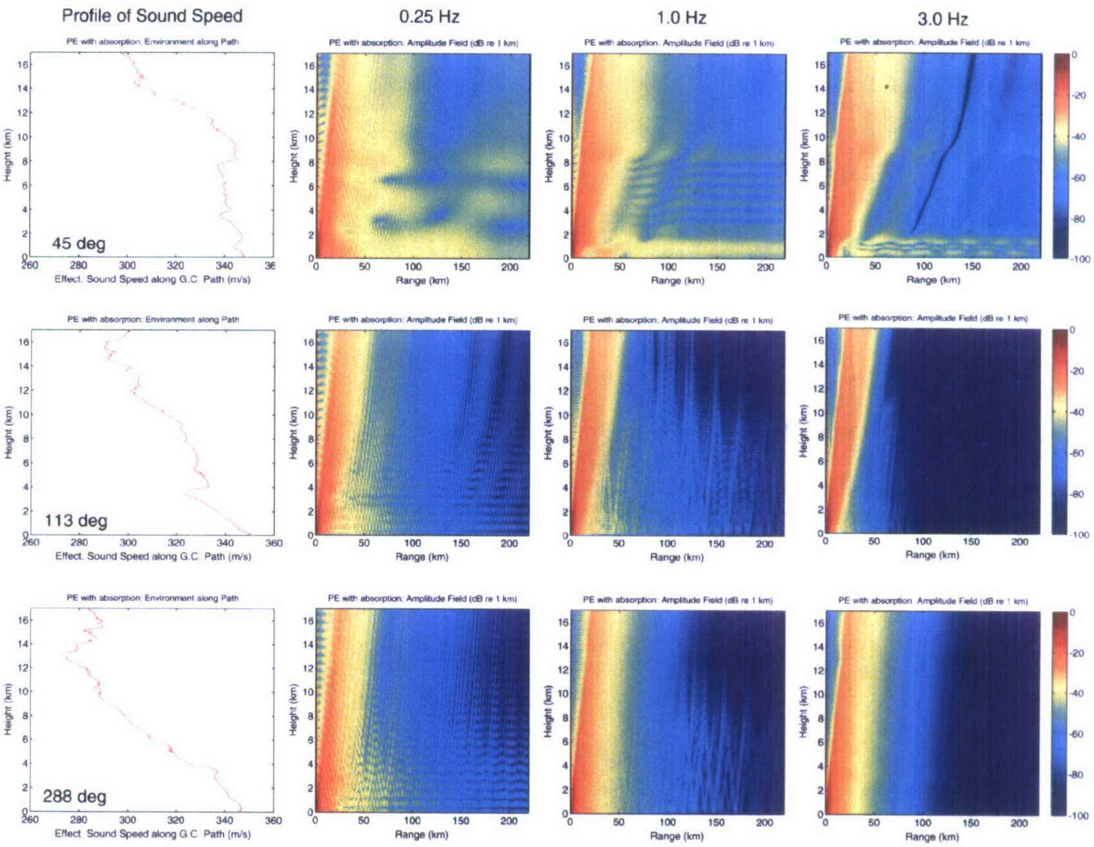

Figure 11. One example of PE modeling for August 6, 2007, 20:00:00 hour. Sound profiles along the three azimuths of 45°, 113°, and 288° are displayed to the left. Energy estimates from the PE calculation as a function of range at frequencies of 0.25, 1, and 3 Hz are plotted to the right.

CONCLUSIONS AND RECOMMENDATIONS

NE China

Seismic data from the Huabei Seismic Network in NE China are being used to improve crust and upper mantle models for NE China, supplementing data gathered from portable instrumentation deployed in the region as part of this project. Analysis of teleseismic body and surface waves from 21 events recorded by this network has been completed with the extraction of teleseismic receiver functions and phase velocity estimates across the network. Work continues to include this new data source in estimating the crust and upper mantle structure in the region.

Infrasound

Preliminary data analysis of regional infrasound observations from four large explosions shows three major results: (1) Infrasound arrivals at local (<100 km) and regional distances (150–210 km) with group and phase velocity estimates constraining the propagation paths-local arrivals (<100 km) are related to the propagation in the near

surface and regional arrivals (150–210 km) are turning rays at higher altitude. (2) There were significant differences in amplitude and signal complexity of the observed seismo-acoustic signals for the four identical explosions detonated on four different days. (3) Modeling based on the PE method, using local atmospheric profiles based on empirical data, predicts trapped acoustic energy, which explains the infrasound arrivals and focusing of energy at local distance range (<100 km).

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